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DUCTILE THIN SHEETS FOR BLAST RETROFIT

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14. ABSTRACT

Blast resistant design has come to the forefront of engineering concerns in the wake of recent terrorist threats to the United States. Safety and security are of utmost concern when designing structures, and there has been a significant rise in the demand for researching new methods of reinforcing and retrofitting structures to provide better resistance to blast loadings. The focus of this paper is on the use of thin sheets as a method of such retrofits. Research is done to ascertain the sheets strength, analyze the response of the sheets to the application of static pressure, explore strength and ductility limits, investigate connection details, and develop an analytical model for defining the materials static resistance function, which will be verified by experimental data. The analytical model for the resistance function will be used in a single-degree of freedom (SDOF) dynamic model to predict the response of the sheathings in a blast-retrofitted wall system.

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Ductile Thin Sheets for Blast-Retrofit

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ABSTRACT

Blast resistant design has come to the forefront of engineering concerns in the wake of recent terrorist threats to the United States. Safety and security are of utmost concern when designing structures, and there has been a significant rise in the demand for researching new methods of reinforcing and retrofitting structures to provide better resistance to blast loadings. The focus of this paper is on the use of thin sheets as a method of such retrofits. Research is done to ascertain the sheets' strength, analyze the response of the sheets to the application of static pressure, explore strength and ductility limits, investigate connection details, and develop an analytical model for defining the materials static resistance function, which will be verified by experimental data. The analytical model for the resistance function will be used in a single-degree of freedom (SDOF) dynamic model to predict the response of the sheathings in a blast-retrofitted wall system.

INTRODUCTION

Massive infill walls, such as concrete masonry unit (CMU) walls, have low resistance to blast loading and fail catastrophically under blast pressure. A wall's ability to resist the energy imparted by a blast is vital to its structural robustness. These massive infill walls have very little energy absorption capabilities and may produce hazardous projectiles during an explosion, thus causing destruction and injury to the people or property the walls were designed to protect. Therefore, a blast-retrofit system is needed to increase the strength and ductility of the walls, and prevent debris from entering a room. Spray-on and trowel-on polymers have proven to be successful in providing the necessary ductility and energy absorption capability (Davidson et al., 2004). In this paper, however, thin sheets will be evaluated as a means of facilitating the need for increasing the ductility and energy absorption of infill masonry wall systems.

This research will determine various properties of a multitude of thin sheets, i.e. strengths, ductility, responses to different connection methods, and pressure-deflection relationships, as they pertain to the blast-retrofit design of a wall system. The specific objectives of this effort are as follows:

- Analytically predict the response of the sheets to static pressure
- Experimentally verify the static response from analysis using a series of coupon, component, and connection tests for a selected number of materials
- Develop adequate connection design for the sheathings
- Develop a final analytical/experimental static resistance function for the sheet systems and implement them in a user-friendly computer code for blast-retrofit design.

APPROACH

To accomplish the aforesaid objectives, an analytical model describing the response of the wall system to static pressure was developed. The analytical model assumes that the static resistance of the wall system is provided by the sheets, whereas the CMU wall provides the inertial resistance. Thus, the analytical model is developed to predict the pressure-deflection function for the thin sheet alone.

For the experimental section, various tests will be conducted for the sheets; component beams, coupons, and connection details. Testing parameters will include varying the sheet materials, bolted connection types, thicknesses of sheet material, and varying the connection parameters, i.e. bolt spacing and thickness of the connection plates. The response of the component beams to pressure will be recorded and used to build the experimental static-resistance functions. These will be compared to the analytical model to verify the analytical predictions.

ANALYTICAL MODELING

At the onset of this project, the primary task was to develop an analytical model of the pressure vs. deflection curve, or the static resistance function of a sheet retrofit. Since little was known about the material behavior of the sheets under uniform pressure, two methods of analytical modeling were explored. The first was an approximate model based on the assumption that the material behavior would be first linear elastic and then perfectly plastic for steel sheets (Kennedy 2005). This method utilized linear elastic equations and a typical equation for a perfectly plastic steel member. But the approximate approach did not lend itself to the exploration of a multitude of materials. The second analytical method, which lends itself to a variety of materials, is a detailed analytical model in which an exact equation relating pressure to deflection is derived. Only the second method will be discussed further in this paper.

DETAILED ANALYTICAL MODELING METHOD

The detailed analytical model follows three principle steps for the derivation of the relation between pressure and deflection. Before the derivation commences, it is necessary to start with an assumed deformed shape for the sheet component beam. After the deformed shaped has been established, the first step of the derivation is to explore equilibrium expressions to investigate load-stress relationships. Secondly, a constitutive relation between stress and strain is used to arrive at a relationship between pressure and stress. Next, a compatibility relationship between deflection and strain is analyzed, ultimately resulting in the desired relationship between pressure and deflection. This process is outlined through the flowchart in Figure 1.

Based on the assumption that the deflection curve is parabolic in nature:

$$y(x) = \Delta\left(1 - 4\left(\frac{x}{L}\right)^2\right) \qquad (1)$$

In this analytical derivation, the strain was assumed to be uniform along the length and thus the stress and the resultant internal tension membrane force *T* are also assumed uniform. In reality the internal resultant tensile force *T* varies along the length of the steel sheathing and depends on its location along the length:

$$T(x) = \frac{p\xi L}{\sin(8\delta\xi)}$$

Where $\theta(x) = y'(x)$; $\delta = \Delta/L$; and $\xi = x/L$. For small values of Δ the variation of *T* is very small, whereas for larger values of Δ the value of *T* can increase by approximately 10%. Therefore, the variation of *T* along the span will be assumed constant and will take the value at the ends of the beam (x/L = 0.5).

Next, equilibrium equations are applied to the free body diagram of Figure 1.

$$\Sigma F_y = 0$$
$$2\,T\sin(\theta) = wL \qquad (2)$$

For small angles, $\sin(\theta)$ can be approximated as simply θ, which is also equal to y'. Furthermore, *T* can also be rewritten as σA. This means that Equation 1 can be rewritten as

$$\left(\frac{8\sigma A}{L^2}\right)\Delta = w$$

Note that for a unit width, $b=1$, the area, *A*, would be equal to $bt = t$, and the distributed load *w* would be simply $w = pb = p$, where *p* is the pressure. From substituting these conditions into the above equation, the following expression is achieved:

$$p = \frac{8\sigma \quad t}{L^2}\Delta \qquad (3)$$

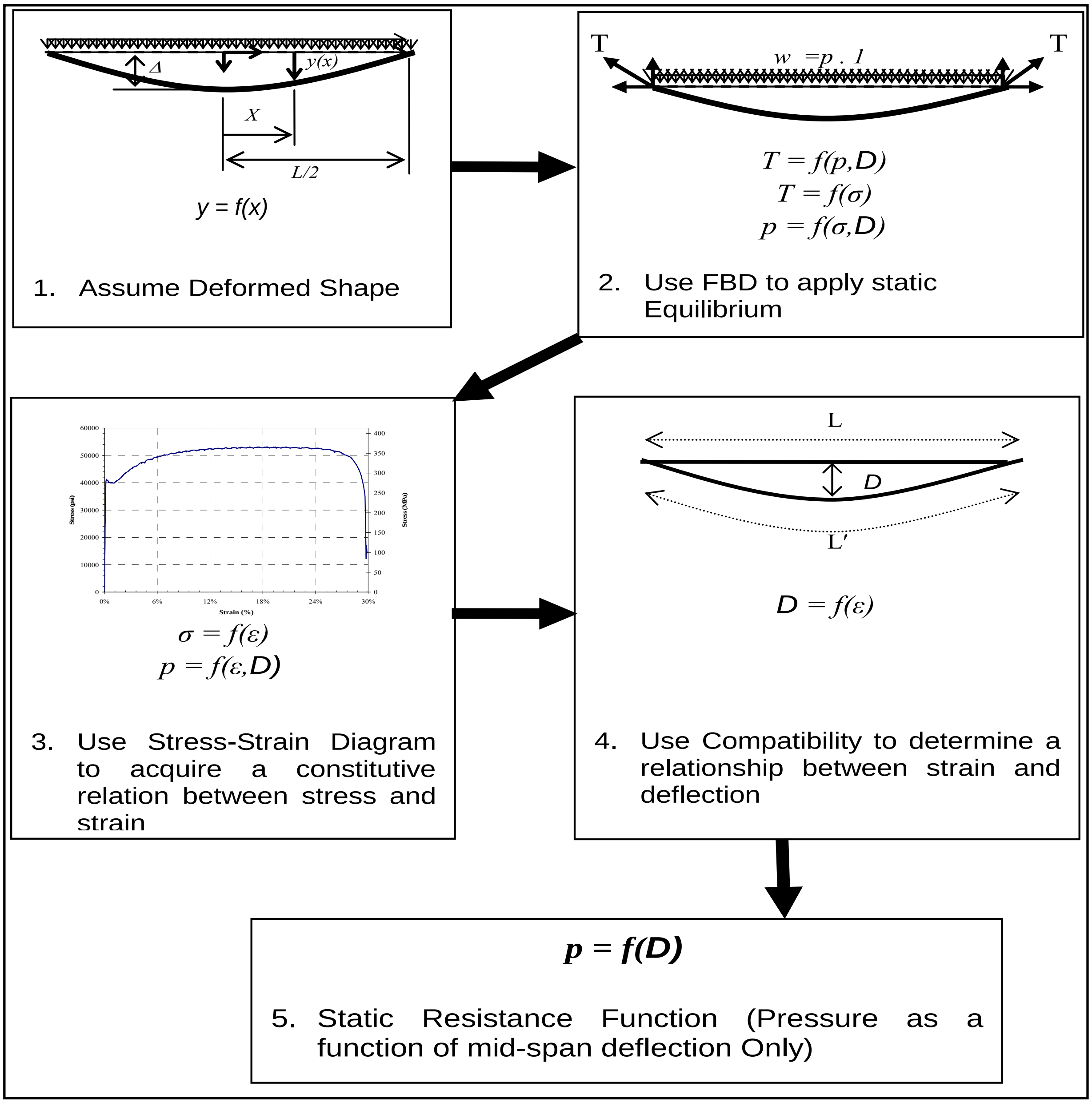

Figure 1 Analytical Model Flowchart

Next, a relationship between Δ and σ is investigated through the constitutive relation of the material (stress-strain diagram). Consider the stress-strain curve for typical sheet materials shown in Figure 2.

It is necessary to use compatibility to find a relation between the strain and deflection. Once the exact strain is determined from this relationship, the corresponding stress can be found from a stress-strain diagram, and Equation 3 is used to determine the pressure at that deflection. Thus, a relationship between pressure and deflection is established. This process is outline next.

Consider the deflected steel sheet in Figure 1. Assuming that the strain is uniform along the length of the beam, it is known from the definition of strain that

$$L' = (1+\varepsilon)(L) \tag{4}$$

Additionally, it is also known from arc properties that the arc length can be given by

$$ArcLength = \int_0^L \sqrt{1+(f'(x)^2)}$$

Solving the integral using the integration limits, and back-substituting it can be shown that

$$L' = 2\left(\frac{8\Delta}{L^2}\right)\left[\frac{\frac{L}{2}\sqrt{\frac{L^2}{4}+\frac{L^4}{64\Delta^2}}}{2} + \frac{L^4}{128\Delta^2}\ln\left(\frac{L}{2}+\sqrt{\frac{L^2}{4}+\frac{L^4}{64\Delta^2}}\right) - \left(\frac{L^4}{128\Delta^2}\ln\left(\frac{L^2}{8\Delta}\right)\right)\right] \qquad (5)$$

The following summarizes the steps to determining the detailed analytical model for calculating the load-deflection response of the sheets:

1. Set Δ equal to zero, and incrementally increase its value by a small amount
2. Use Equation 5 to determine the corresponding value for L'
3. Use Equation 4 to calculate the strain
4. From the stress-strain curve (similar to those in Figure 2), find the stress corresponding to the calculated strain
5. Use Equation 3 to calculate the pressure
6. Increment Δ and start at step 1 again. Repeat the process until the ductility limit is reached, which represents failure of the steel sheet.
7. Plot the calculated pressures versus the incremented deflections to failure

Using the procedure described above, an analytical static resistance function is produced. The variation of the tension membrane force and its components with respect to the end rotation in the steel sheet are shown in Figure 3.

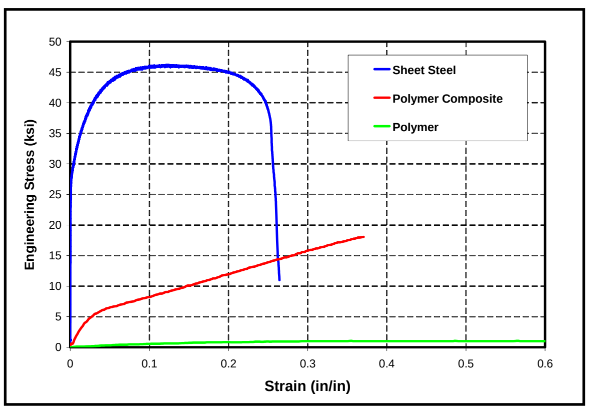

Figure 2 Constitutive Relationship (stress-strain)

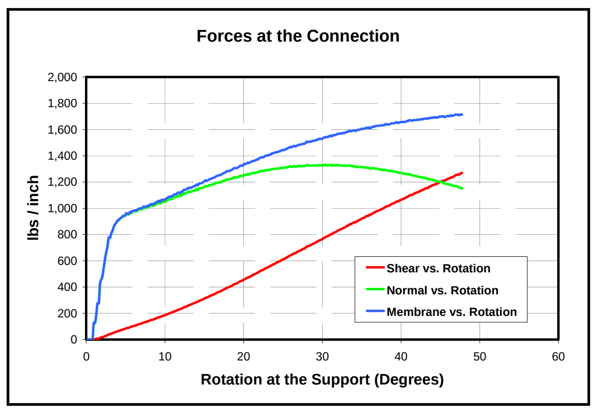

Figure 3 Forces with Respect to End Rotation

EXPERIMENTAL EVALUATION

To validate the derivation of analytical resistance function experimentally, coupon-, connection-, and component-level tests were performed. Coupons were cut from similar materials as the component beam and connection specimens used in this study followed ASTM standards. The stress-strain relations of sheets were measured to develop the analytical static resistance function in conjunction with connection and component testing. Figure 2 showed the engineering stress-strain relationship between three evaluated sheet materials. The three materials were steel, a composite polymer, and a polymer sheet.

For the connection testing, polymer and steel sheathing samples were connected to a loading frame using steel clamping plates as seen in Figure 4. The samples were pulled in tension until failure. The steel sheathing was tested in three different gage thicknesses: 18, 20, and 22. With regard to connection details, the following parameters were tested: 8, 12, and 16 inches bolt spacing; ¼ and ⅛ inch thickness of the clamping plate. Similarly the polymer sheets were tested.

Figure 4 Connection Testing

For the component beam testing, a setup was designed using a 16-point loading tree that imposes simulated uniform load across the length of the beam. All three sheathing samples were connected at the ends and loaded in bending until failure (Figure 6). Load and deflection were recorded and the typical results are shown in Figures 5 & 7 along with their corresponding analytical predictions.

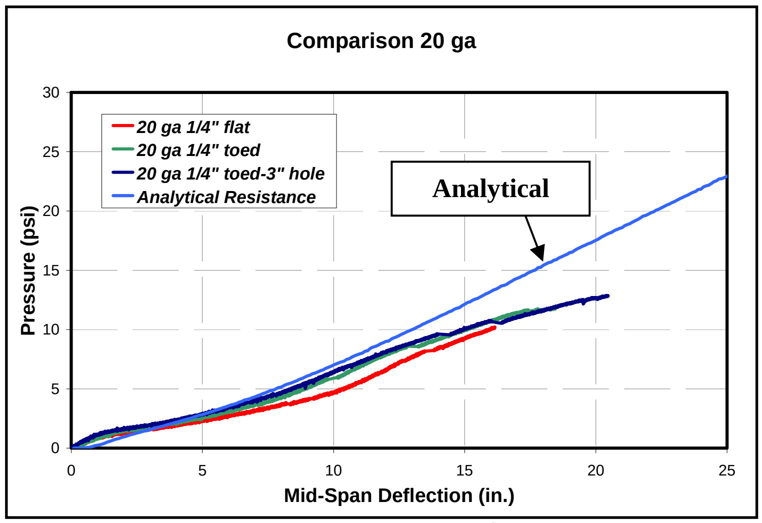

Figure 5 Resistance Function of Steel Sheets

Figure 5 shows the comparison of three steel sheet systems. All shown experiments were of 20 ga. material tested with ¼ inch flat connection plates. Two experiments used a toed connection plate; the toed plate has come about in an effort of combating the shear failure that was present in previous research along the leading edge of the steel sheet and connection plate. In addition, one toed experiment had a 3 inch reduction in the cross section towards the center of the span in an attempt to reduce the membrane forces and promote yielding of the sheathing to gain additional energy absorption. The analytical model does not take into the account the bending of the connection plates that was experienced on every test. The bending of the connection plates adds additional energy absorption into the system, but the bending of the connection plate also redistributes the membrane forces directly to the bolt holes. When the loading reaches this stage, bolts bear at the connection; tearing of the sheet is shortly followed. A balance of reducing the cross sectional area of the sheet and forces at the connection must be further refined to get the optimum retrofit. Figure 6 shows the toed connection and general component beam test.

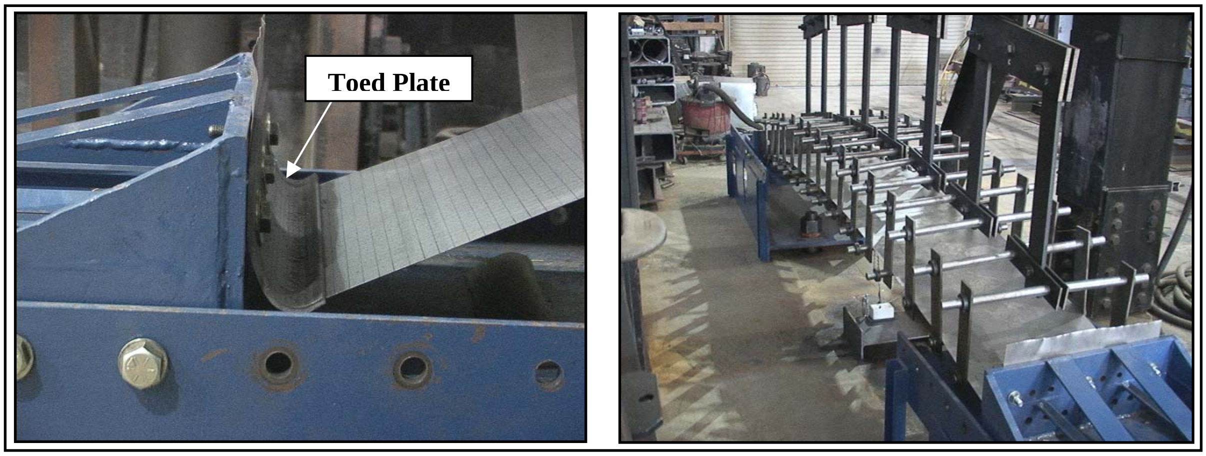

Figure 6 Experimental Testing of Steel Sheets

In the initial stages of evaluating this polymer composite, it was discovered that mechanical connections would again be needed. Initial testing focused on the usage of chemically bonding the composite to steel and concrete. Figure 7 gives three examples of the composite experiments varying the clamping plate thicknesses. The thinner clamping plate yields prematurely, and this yielding opens the connection up allowing the membrane forces to be directly distributed to the bolt hole. As a result of this redistribution, the sheet is never allowed to gain greater loads, similar to the steel sheet. The ¼ and ⅜ inch thickness plate did not catastrophically yield, which allows for the membrane forces to pickup until the forces overcome the clamping pressure of the connection plates to end supports in slip-critical behavior.

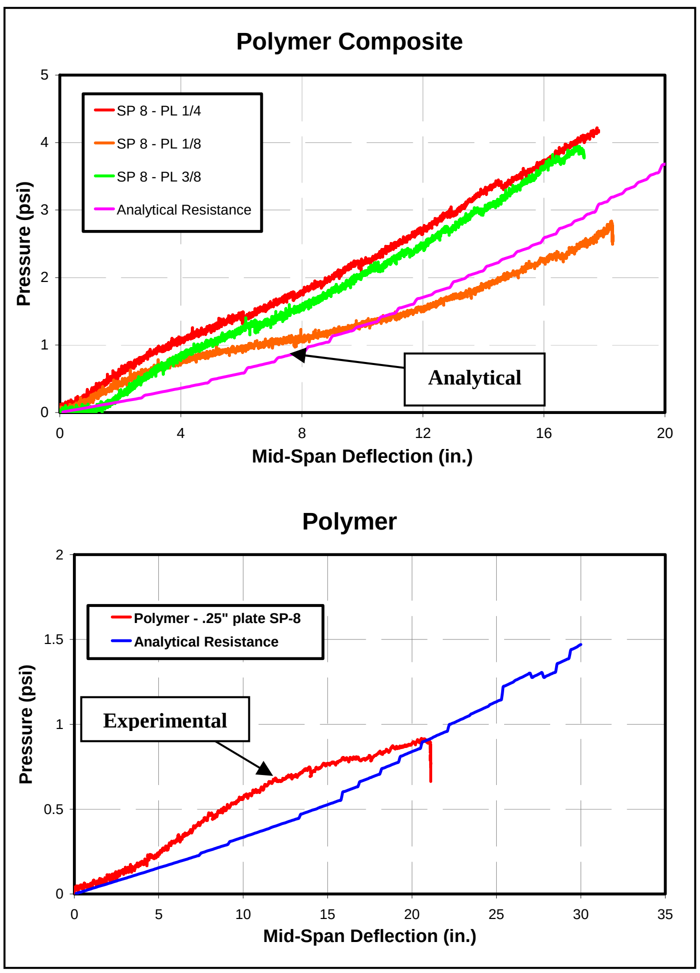

Figure 7 Resistance Function of Polymer Composite and Polymer Sheets

The three experiments in Figure 7 show that the ¼ and ⅜ inch plates have similar behaviors, but as seen in the right of Figure 8 the ¼ inch thick connection plate does show some deflection. It is hypothesized that a medium in the connection resistance and the membrane forces have been reached.

The third material evaluated for this paper is a very ductile homogenous polymer. Figure 7 shows the analytical comparison between the experimental testing of the polymer. Due to the low stiffness of the material, no failures were achieved in the experimental testing. It was observed that the polymer began to yield un-uniformly, demonstrating strain hardened sections and un-yielded sections along its length. The result was a stiffer resistance than what was analytical predicted.

Though the polymer had a very low modulus compared to steel or the polymer composite material. The ⅛ inch connection plates still began to yield allowing for the polymer to load around the bolt holes in the material. No failures at the bolt holes were observed due to the testing apparatus not being able to supply additional strains. But it is thought that a ¼ inch plate should still be used as a minimum thickness in application with this material.

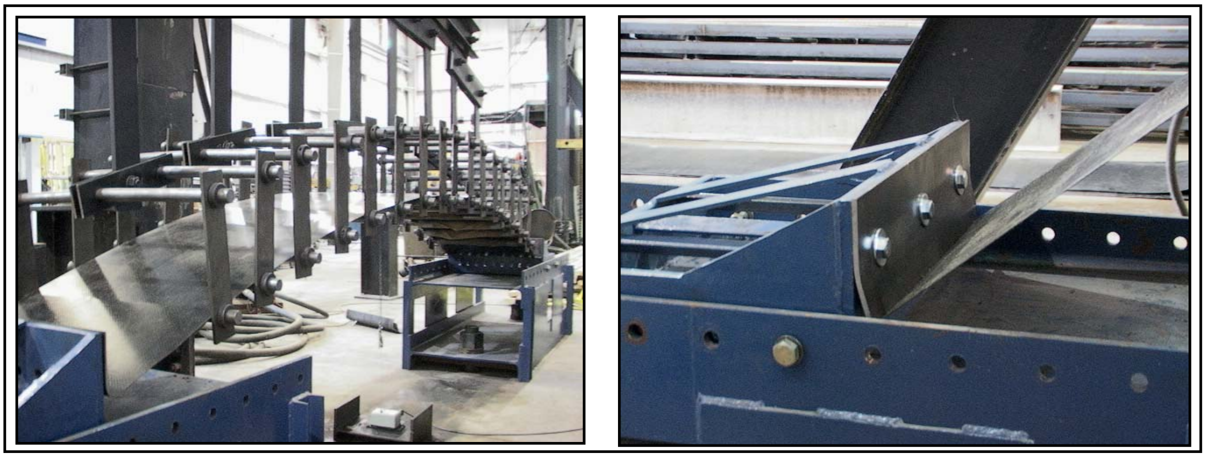

Figure 8 Experimental Testing of Polymer Composite

BLAST-RETROFITTED WALL EXAMPLE

To illustrate the research effort outlined in this paper, an example of a 12-foot high unreinforced CMU wall retrofitted with 20-gage steel sheets, 0.043 inch thick polymer composite, and ⅛ inch thick polymer anchored top and bottom using 6 inch by ¼ inch steel plates and ⅝ inch bolts spaced at 12 inches, 8 inches, and 16 inches respectively on centers. The CMU wall is assumed to respond in one-way bending with compression arching and added inertial resistance to the blast. The ductility capability of the wall system is mainly contributed by the tension membrane resistance of the un-bonded sheet retrofits. The analytical material responses of the sheets with the superimposed arching resistance are shown combined as the composite resistance functions in Figure 9. The energy absorbed by the sheets and arching during the blast is related to the area under curve of the load-deflection curve.

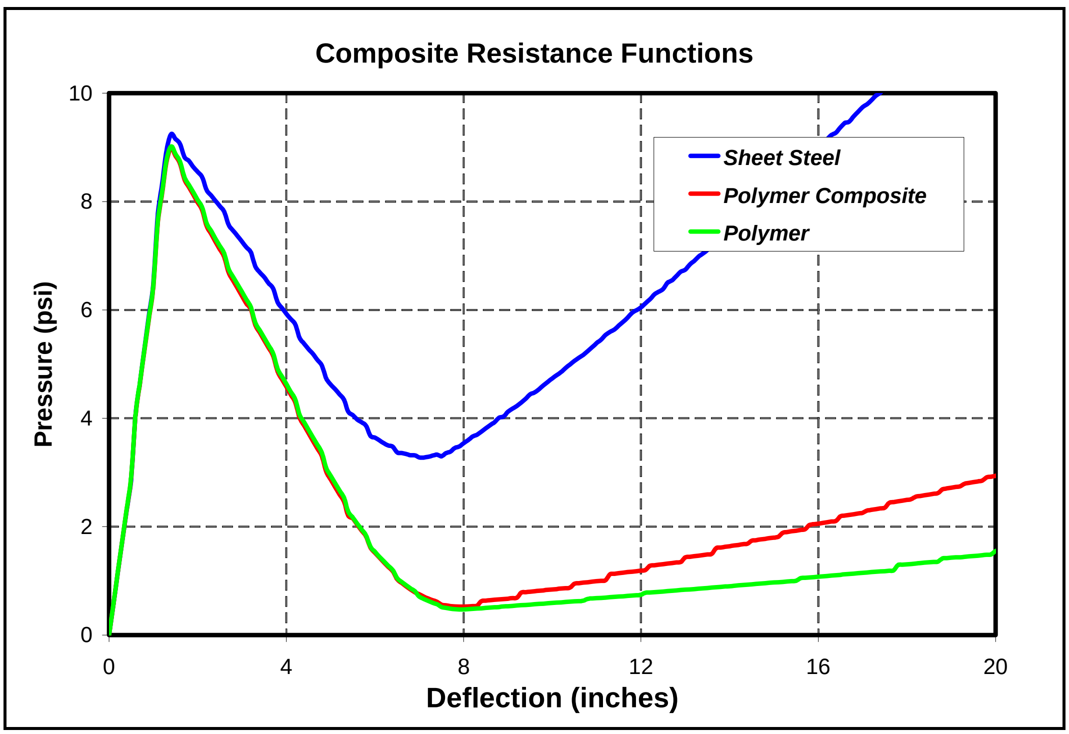

Figure 9 Combined Sheet and Arching Resistance Function

The response of the wall under a planned future test is predicted in this paper. The threat is defined by a reflected pressure of 45 psi and a reflected impulse of 220 psi-msec. Figure 10 is the loading curve used in this example; the negative phase was included.

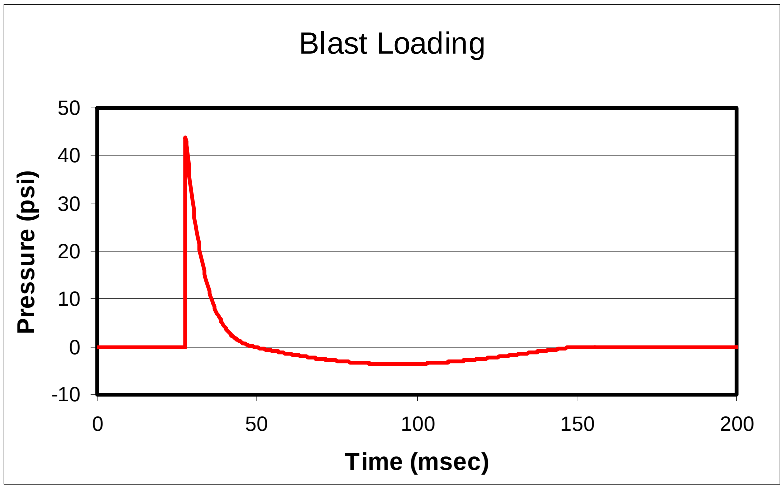

Figure 10 Loading Curve

The analytical static resistance functions were used in a SDOF dynamic model to predict the dynamic response of the blast-retrofitted wall under above loading; their responses are shown in Figure 11. According to the component beam tree tests, the steel, polymer composite, and polymer sheets,` all deflected within their physical system capability. Therefore, it is expected that these CMU wall sheet retrofitted systems would all survive.

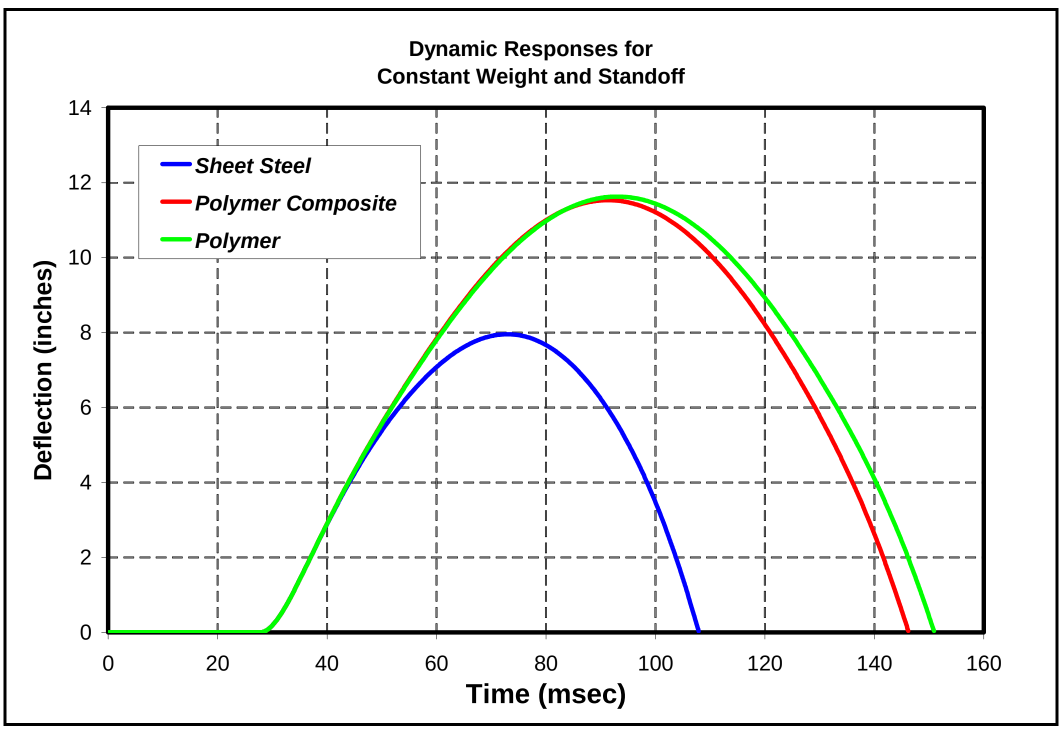

Figure 11 Predicted Response of Materials Under Similar Loadings

DISCUSSION

The analytical model developed in this paper matches closely the experimental resistance functions. The resistance function traces the behavior of the sheet during the elastic, plastic, strain hardening, and softening regions of the response to failure. The resistance of the retrofitted wall is provided by the CMU block inertia, compression arching of the blocks and the tension membrane resistance of the sheets. The resistance of the sheet is ultimately limited by the capacity of their connections, and thus the clamping plate and concrete anchors should be designed to prevent premature failure at the ends. Proper combination of anchorage and plate dimensions is necessary to utilize as much as practically possible the capacity of the sheets and to increase the ductility and energy-absorption capabilities of the wall.

The analytical resistance function is combined with a SDOF model to predict the response under blast loadings. This procedure and modeling is being developed for use in a PC-based code for blast resistant design. Further research is needed to define full-scale experiments for validating the code and model.

REFERENCES

Biggs, J.M., 1964, "Introduction to Structural Dynamics." McGraw Hill College.

Davidson, J.S., Porter, J.R., Dinan, R.J., Hammons, M.I., and Connell, J.D., "Explosive Testing of Polymer Retrofit Masonry Walls," ASCE Journal of Performance of Constructed Facilities, 2004 Vol. 18, No. 2.

Fitzmaurice, J., 2006, "Blast Retrofit Design of CMU Walls Using Polymer Sheets," MS Thesis - University of Missouri, Columbia, MO.

Kennedy, J., 2005, "Analytical and Experimental Evaluation of Steel Sheets for Blast Retrofit Design," MS Thesis - University of Missouri, Columbia, MO.